REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave Blank*)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	August 29, 1996	FINAL 1 Feb 1996 - 30 Aug 1996

4. TITLE AND SUBTITLE

Numerically Efficient Rotorcraft
Trim and Transient Response

5. FUNDING NUMBERS

DAAJ02-96-C-0012

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8. PERFORMING ORGANIZATION REPORT NUMBER

ART96-0001

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Aviation Applied Technology Directorate
U.S. Army Aviation and Troop Command
Fort Eustis, VA 23604-5577

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Unclassified/Unlimited

20010523 134

13. ABSTRACT (*Maximum 200 words*)

Comprehensive rotorcraft analysis systems are valuable tools in the design and analysis of rotorcraft. To make rotorcraft analyses a more practical tool for routine use, the long runtimes of analyses must be reduced. A central computational issue is the problem of solving for the rotorcraft trim and transient response. As a result of this limitation in the analysis of systems with a large number of degrees of freedom, the goal of this phase I effort is to develop a prototype for numerical algorithms for efficient trim and transient response. The effort includes three steps to reduce the runtime: 1) Using the periodicity of a multibladed rotor to develop an identical blade algorithm to reduce the number of trim calculations, 2) Creating a reformulated element for 2GCHAS to allow efficient modal reduction and the use of the identical blade algorithm, and 3) Utilizing modal reduction to reduce the order of the model, thus reducing the runtime of the trim and transient response calculations. Algorithms for these steps have been successfully developed and enable systems such as 2GCHAS to perform analyses more efficiently. This efficient trim and transient response analysis broadens the scope of rotorcraft problems that can be analyzed in a reasonable amount of time.

14. SUBJECT TERMS

Trim, Transient Response, Second Generation Comprehensive Helicopter Analysis System (2GCHAS), Helicopter

15. NUMBER OF PAGES

23

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	Unlimited

SBIR PHASE I FINAL REPORT

Numerically Efficient Rotorcraft Trim and Transient Response

Contract No. DAAJ02-96-C-0012

August 29, 1996

Project Summary

Comprehensive rotorcraft analysis systems are valuable tools for engineers and researchers to use in the design and analysis of rotorcraft. To make rotorcraft analyses a more practical tool for routine use, the long runtimes of the analyses must be reduced. A central computational issue in any comprehensive rotorcraft analysis code is the problem of solving for the rotorcraft trim and transient response. As a result of this limitation in the analysis of systems with a large number of degrees of freedom, the goal of this phase I effort is to develop a prototype for numerical algorithms for an efficient trim and transient response. The effort includes three steps to reduce the runtime and are as follows: 1) Using of periodicity of a multi-bladed rotor to develop an identical blade algorithm to reduce the number of computations in trim calculations, 2) Creating a reformulated element (or super element) for 2GCHAS to allow efficient modal reduction and the use of the identical blade algorithm, and 3) Utilizing modal reduction to reduce the order of the model, which will in turn reduce the runtime of the trim and transient response calculations. Algorithms for these three steps have been successfully developed and enable systems such as The Second Generation Comprehensive Helicopter Analysis System (2GCHAS) to perform analyses more efficiently. This efficient trim and transient response analysis broadens the scope of rotorcraft problems that can be analyzed in a reasonable amount of time.

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Introduction

Even with today's powerful computers, sophisticated comprehensive rotorcraft analyses require extremely long runtimes. The runtimes must be reduced in order for the analyses to be a practical, useful tools for routine use by engineers and researchers. One of the key issues involved is the inefficiency of solving for rotorcraft trim and transient responses. Solving for rotorcraft trim and transient response is the central issue of any comprehensive rotorcraft analysis code. The rotorcraft performance, loads, and vibration are obtained from the trimmed periodic solution of the rotorcraft equations of motion that can have coupled rotor-fuselage-propulsion-control systems. The stability analysis and control design are also based on the perturbation equations about the same trimmed and periodic solution. Due to the importance of reducing the runtime for comprehensive rotorcraft analyses, an efficient method of trimming a rotorcraft system and generating the transient response has been developed.

The three steps taken to develop a numerically efficient rotorcraft trim and transient response algorithm include the following: 1) Taking advantage of the periodicity of a multi-bladed rotor to reduce the number of computations by at least a factor of the number of blades. 2) Integrating a reformulated element (super element) in 2GCHAS using the User Defined Element which reduces the computation time by requiring that the system matrices for mass, damping, and stiffness be calculated only once. The super element also enables efficient modal reduction and identical blade algorithm implementation in 2GCHAS. 3) Utilizing modal reduction to establish a sufficiently accurate reduced order model to find the rotorcraft trim and transient response.

The prototype coding for the steps listed is complete. The code is tested by comparing results from the new code with base line results for various models. All three steps produce accurate results and lead to more efficient rotorcraft analysis. The goal of this contract is to produce a numerically efficient rotorcraft trim and transient response algorithm, and the goal is met with the reduction in computational time being more than $1/n$th of the original computational time when n is the number of blades in the system.

The current capabilities of comprehensive rotorcraft analysis are discussed in the Technical Background section, while the algorithms for each of the steps toward efficient trim and transient response solutions are discussed in detail in the section Technical Approach. The accuracy of the algorithms as investigated in 2GCHAS and FLIGHTLAB are discussed in the section Numerical Results - Accuracy and in the section Numerical Results - Efficiency, the improved savings in CPU is addressed. The items to be addressed in the future are listed in the Scope of Future Work section, and the report is concluded with the Discussion and Conclusion section.

Technical Background

Today's sophisticated comprehensive rotorcraft analyses are required to model complex rotorcraft configurations with non-linear structures and unsteady airloads with distorted free vortex wake and dynamic stall, Refs. 1 to 5. For accurate representation of the non-linear structures, finite element methods are generally used, Refs. 1. This results in a very large and complicated aeroelastic system. The degrees of freedom for a typical single multi-bladed rotor can be as large as several hundred. The methodologies applied to solve this type of non-linear dynamic system falls into two main categories. One is time integration with Newton-Raphson such as in 2GCHAS, Ref. 6. The other is the method of weighted residuals, such as finite time elements, Refs. 5 and 7. The Fourier series method (harmonic balance) is a special case of p-versions finite time element. The method of weighted residuals is a valuable tool for solving a periodic system. But, the size of the matrices can become too large to be efficiently solved when there are a large number of degrees of freedom. For example, in using the Fourier series method for a 400 degree of freedom system, the size of the matrices for the solution will be 6,800 X 6,800 if only eight harmonics are used for each degree of freedom. Moreover, the calculation of the matrices' elements is numerically formidable. Since there is always hidden dependency of the aerodynamics on structural degrees of freedom and the non-linearity of the system, even in the Fourier series approach, iteration is required. This is why a current comprehensive rotorcraft code computes transient response using an implicit time integration scheme and solves a set of non-linear equations at each time step, Ref. 1. But there is a numerical efficiency problem with the time integration too. It often takes long runtimes to converge to the periodic solution. This is especially true when the systems have less damped degrees of freedom.

General theoretical formulations for the rotorcraft trim can be found in Refs. 6 and 8. There is, however, a lack of fully developed or tested numerical algorithms for efficient trim and transient response for the system with a large number of degrees of freedom. The practical application of comprehensive rotorcraft analyses is in need of such an algorithm, and this has been the focus of this contract.

Technical Approach

Three independent steps have been taken to develop a more efficient rotorcraft trim and transient response that can be used in 2GCHAS and other comprehensive rotorcraft codes. The steps are to utilize the periodicity of a rotorcraft system in the integration algorithm, to introduce a super element specific for 2GCHAS, and to reduce the order of the model. The identical blade algorithm improves the efficiency of trim calculations, while the super element and reduced order model improve the efficiency of both the trim and transient response calculations.

Identical Blade Algorithm

As mentioned above, the first step in improving the trim calculation efficiency is to utilize the periodicity of the blade response. 2GCHAS currently supports an identical

blade algorithm for a fixed hub only, while the algorithm described here applies to a moving hub model. Also, an identical blade algorithm has never been applied to finite element code before. The purpose of the algorithm is to reduce the computation time of the rotor response, and the developed identical blade algorithm does exactly this. The algorithm takes advantage of the fact that each blade (assuming all blades are identical) will exhibit the same response as the first blade with a constant phase shift. Therefore, once the response of the first blade is known, the response of the remaining blades and their effects on the system are known. With the response of the remaining blades known without any calculations, the matrix to invert in Equation (2.3-18) in the *2GCHAS Theory Manual* has been reduced and the trim computational time is less than $1/n$th the original computational time.

The identical blade algorithm developed considers only one blade and then replaces the remaining blades with forces and moments equal to their internal nodal reactions applied at the hub. The reduced equations duplicate the unreduced equations exactly. When the blade root internal loads are applied at the hub, the contribution of individual degrees of freedom to the hub equations do not need to be computed. Instead, they are implicitly considered in the blade root internal loads.

This algorithm may be applied to models with multiple rotors, as well as models with a fuselage. As mentioned above, the approach includes analyzing a single blade, and its results are then mapped onto the remaining blades. The user inputs the structural model required for a single blade of each rotor and a fuselage. The analysis is performed for the model with a single blade and then the multiblade effects are included by applying the blade root interal loads to the hub at the corresponding azimuthal location for the remaining blades (blades 2 through n for an n-bladed rotor). In this single blade analysis which utilizes periodicity, the internal loads (internal nodal reactions) of blades 2 through n are known from the past response of blade 1.

During the time integration of the first rotor revolution, the internal loads for blade 2 through blade n are unknown, but cannot be ignored as the response of the system may diverge due to the centrifugal force generated by blade 1. A start-up procedure is therefore needed. To prevent the divergence due to the centrifugal force, the hub motion is set to zero, and the solution is generated for each time step in the first revolution. The internal loads of blade 1 are stored and used for the internal loads of the remaining blades. After the first revolution, the hub motion constraint is removed and the blade root interal loads for all blades are applied to the hub. The internal loads are calculated from the following equation:

$$Q = M_e \ddot{x}_e + C_e \dot{x}_e + K_e x_e - F_e \tag{1}$$

where Q is the internal load, M_e, C_e, and K_e are the mass, damping, and stiffness matrices of the rigid blade or blade element connected to the hub, F_e is the sum of the applied external and nonlinear forces, and the degrees of freedom are represented by x_e. This approach assumes that the blades of each rotor are identical. The single blade method may be applied to multirotor systems, and the rotors may have a different number of blades. For the simplicity of the current algorithm, if the single

blade method is designated by the user, the method will be applied to all the rotors in the model, excluding the auxilary rotors.

Super Element Development Using UDE in 2GCHAS

The second step to improve efficiency is to integrate a "super element", or reformulated element, for the hingeless rotor into 2GCHAS. The element is similar to FLIGHTLAB in its treatment of non-linear beam elements, and is generated in 2GCHAS using the User Defined Element (UDE). The UDE is used for prototyping only as a proof of concept for the new super element. With the full implementation of the super element in 2GCHAS, the hingeless rotor will be a new element, not included in the UDE as is currently the case. To reduce the coupling between the degrees of freedom, as well as to reduce the non-linearities in the system equations, the axial degrees of freedom are replaced with elongational degrees of freedom, and a element coordinate system is used instead of the blade root coordinate system. The degrees of freedom in the blade root coordinates (currently used in 2GCHAS) are shown in Figure 1, while the degrees of freedom used in the developed super element are shown in Figure 2. With the transition to the degrees of freedom in the element root coordinates, the system becomes more suitable for the use of modal reduction, and the problem with convergence for the non-linear beam identical blade algorithm will be eliminated.

Within the UDE, the system mass, damping, and stiffness matrices are generated only once using the perturbation method, unlike the current 2GCHAS approach in which the element matrices are calculated at each time step. The system generalized forces are then calculated, and the resulting non-linear reaction force vector is found. The force vector is then passed back to 2GCHAS code where it is saved in the RDB. The layout of the UDE is shown in Figure 3. The UDE currently supports a single blade with as many as 10 elements. One of the elements may be a pitch bearing, which may include a spring and damper. The control input to the pitch bearing is from the swashplate. The UDE also supports the use of a lag damper. The damper is attached at the hub and at the end of the pitch bearing element. In the future, the hingeless rotor in the super element will include torque offset, precone, droop, swept tip, and a pitch link model.

With the implementation of a super element in 2GCHAS, the identical blade algorithm can be used with non-linear beam elements, and modal reduction can be implemented with fewer non-linearities and less coupling between degrees of freedom than is currently available. Also, the introduction of the super element reduces the computational time even without modal reduction or identical blade analysis, because the system matrices (M, C, and K) are calculated only once.

Reduced Order Model

The third step toward a more efficient trim and transient response solution is to reduce the model degrees of freedom. Modal reduction exists in the current 2GCHAS, but some problems arise with its use. For example, as the number of modes increases to approximately 10, the benefits of utilizing modal reduction is outweighed by the

computational time required to form the system equations. Also, for reasonably accurate lower frequency mode results, a few higher frequency axial modes must be included. The choice of modes is difficult, and can also greatly affect the results, Ref. 9. These problems with the current 2GCHAS modal reduction can be eliminated by implementing modal reduction through the super element. As mentioned above, the super element implements the element root coordinate system and replaces axial degrees of freedom with elongational degrees of freedom. This reduces non-linearities and coupling between degrees of freedom, allowing accurate modal reduction to be utilized.

The modal reduction is performed on the structural finite element degrees of freedom, and by considering a number of modes less than the number of degrees of freedom, the order of the model is reduced. Consider a system in which x_i are the states to be modally transformed, and x_b are the states to be retained. As outlined in Ref. 9, the partitioned blade equation becomes

$$\begin{bmatrix} M_{bb} & M_{bi} \\ M_{ib} & M_{ii} \end{bmatrix} \begin{Bmatrix} \ddot{x}_b \\ \ddot{x}_i \end{Bmatrix} + \begin{bmatrix} K_{bb} & K_{bi} \\ K_{ib} & K_{ii} \end{bmatrix} \begin{Bmatrix} x_b \\ x_i \end{Bmatrix} = \begin{Bmatrix} F_b \\ F_i \end{Bmatrix} \tag{2}$$

The modal state vector, η is formed from

$$x_i = \phi\eta \tag{3}$$

where ϕ is the modal transformation matrix corresponding to the states x_i. The blade states are then transformed by

$$\begin{Bmatrix} x_b \\ x_i \end{Bmatrix} = \begin{bmatrix} I & 0 \\ 0 & \phi \end{bmatrix} \begin{Bmatrix} x_b \\ \eta \end{Bmatrix} \tag{4}$$

Inserting Eq. 4 into Eq. 2 and then multiplying the equation by

$$\begin{bmatrix} M_{bb}^{-1} & 0 \\ 0 & \bar{\phi} M_{ii}^{-1} \end{bmatrix} \tag{5}$$

where $\bar{\phi}$ is a subset of the inverse of the eigenvector matrix that relates to the transformed states. The result is the reduced blade equation.

$$\begin{bmatrix} I & M_{bb}^{-1} M_{bi} \phi \\ \bar{\phi} M_{ii}^{-1} M_{ib} & I \end{bmatrix} \begin{Bmatrix} \ddot{x}_b \\ \ddot{\eta} \end{Bmatrix} + \begin{bmatrix} M_{bb}^{-1} K_{bb} & M_{bb}^{-1} K_{bi} \phi \\ \bar{\phi} M_{ii}^{-1} K_{ib} & \bar{\phi} M_{ii}^{-1} K_{ii} \phi \end{bmatrix} \begin{Bmatrix} x_b \\ \eta \end{Bmatrix} = \begin{bmatrix} M_{bb}^{-1} \\ \bar{\phi} M_{ii}^{-1} \end{bmatrix} \begin{Bmatrix} F_b \\ F_i \end{Bmatrix} \tag{6}$$

Eq. 6 may be written in a more compact form by labeling the first matrix M_m, the second matrix K_m, the states x_m and the generalized forces F_m.

$$M_m \ddot{x}_m + K_m x_m = F_m \tag{7}$$

With the reduction in the number of states in Eq. 7, the runtime of large systems is significantly lessened. Not only is the number of perturbations reduced for the calculation of the system matrices, but eigenanalysis is performed on smaller matrices when modal reduction is applied to the system equations. For example, a large system with 400 states requires 400 * 3 perturbations to find the system matrices. If modal

reduction is utilized and the number of states is, therefore, reduced to 40, only $40 * 3$ perturbations are needed. Also, the eigenanalysis for the model with 400 states will result in an eigenvector matrix that is 800 x 800 versus 80 x 80 for the reduced order model.

Numerical Results - Accuracy

Rigid Blade - 2GCHAS

First, the identical blade algorithm is tested on a model with a rigid fuselage and four rigid blades. The fuselage includes only six degrees of freedom and the rotor includes four DOF (one flap DOF for each blade). The helicopter is in forward flight with uniform inflow. The resulting flap angles for both the identical blade analysis and the full four-bladed analysis are shown in Figure 4. As can be seen in the plots, the identical blade analysis reproduces the results of the multi-blade model, as the flap angles for both cases through one rotor revolution are the same.

Non-linear Beam - 2GCHAS

The non-linear beam problem is not currently successful in 2GCHAS with the identical blade algorithm, as the solution fails to converge. The model has a rigid fuselage and a four-bladed rotor. The hub is fixed through the first revolution of the rotor, as described above in the Technical Approach section. In subsequent rotor revolutions, the forces and moments of the remaining blades are applied at the hub. Once the hub is released however, the solution begins to diverge when run in 2GCHAS. After some investigation, it is believed that the non-linearities in 2GCHAS prevent convergence. As a proof of concept for the non-linear beam case, the identical blade algorithm is applied in FLIGHTLAB, in which the non-linear beam analysis is similar to the implementation of the rigid blade analysis in 2GCHAS.

Non-linear Beam - FLIGHTLAB

The identical blade algorithm in FLIGHTLAB produces results that are in agreement with the results from the full four-blade analysis for non-linear beam case. The model for the non-linear beam case includes a fuselage and rotor with four blades in forward flight, with cyclic input. The model does not include inflow in an effort to minimize the differences between 2GCHAS and FLIGHTLAB codes. The blades are modeled with ten elements and each element has one aerodynamic point. Figure 5 shows the forces and moments at the hub from running the four-bladed rotor model, as well as from running the identical blade rotor model. Within one revolution after the hub is released (again, the hub is fixed through the first rotor revolution), the force and moment results for the identical blade case match the four-bladed case. Shown in Figure 6, the blade flapping results for the identical blade and four-bladed cases are in agreement soon after the hub is released. A similar model has been run with one element per blade, as well as three elements per blade, which both produce results that again show agreement between the identical blade analysis and the four-bladed analysis after the first rotor revolution.

As the results are in agreement between the identical blade analysis and the four-bladed analysis methods, the prototype coding for the identical blade algorithm is complete in 2GCHAS for the rigid blade case and in FLIGHTLAB for the non-linear beam case. The reduction in computational time due to the use of identical blade code is significant and will be discussed in the next section, Numerical Results - Efficiency.

Super Element - 2GCHAS

The accuracy of the super element generated with the UDE is shown by comparing eigenvalues generated by the 2GCHAS super element with the eigenvalues generated by FLIGHTLAB for the same model. The eigenvalues in Table 1 are a result of a single blade with two elements. A pitch bearing is located between the two elements, and includes a rotational spring and damper. The same model is used in both 2GCHAS and FLIGHTLAB to find the eigenvalues shown in the table. The eigenvalues from 2GCHAS match those from FLIGHTLAB out to the fourth significant digit. The same accuracy has been found for a blade with five elements, and a pitch bearing.

Modal Reduction - FLIGHTLAB

The reduced order model is complete using the modal reduction technique described above in the Technical Approach section. The modal reduction is performed in FLIGHTLAB with results that reproduce the response of the four-blade analysis without modal reduction. Also, modal reduction is applied to the identical blade code to generate results that again match the results of the four-blade analysis after the first revolution. The resulting forces and moments at the hub for modal reduction applied to the four-bladed analysis and the identical blade analysis are shown in Figure 7. The flap angle results using modal reduction are shown in Figure 8. The results for the four-bladed analysis without the modal reduction are not shown, as the results are close enough to the four-bladed analysis with modal reduction that the two are not distinguishable from each other on a plot. Modal reduction can therefore be successfully applied to both four-bladed analysis and identical blade analysis. Although the reduction in computational time is not as great as for the identical blade code, it is still significant and is discussed below.

Numerical Results - Efficiency

Identical Blade

The reduction in computational time is great with the use of the reduced order model and the identical blade algorithm. Originally, the runtime with identical blade algorithm was believed to be $1/n$th the time of analysis without the algorithm. The actual reduction, however, can be much greater as described in the Technical Approach section. The savings found in FLIGHTLAB for non-linear beam cases are shown in Table 2. The model includes a rigid fuselage and four blades modeled with non-linear elements and does not include inflow. The system is in forward flight at 104 knots. The Identical Blade algorithm offers the largest reduction in computation time. The model with three elements and three aerodynamic points takes 16.684 minutes to run when using the four-bladed analysis, but only takes 1.830 minutes when using the

identical blade code. The full, four-bladed model with ten elements and ten aerodynamic points takes 154.552 minutes to run, while the identical blade model takes only 9.485 minutes. For this particular case, the identical blade model is completed sixteen times faster than the full, four-bladed analysis.

Modal Reduction

Blade modal reduction also reduces the computational time significantly. The time reduction in FLIGHTLAB is shown in Table 2. Again, the model includes a rigid fuselage with four blades modeled with non-linear beam elements, and is in forward flight at 104 knots. When the blades are modeled with three non-linear beam elements and three aeordynamic points, the runtime for a four-bladed analysis is 16.684 minutes, but is reduced to 5.231 minutes with modal reduction. For the larger system with ten elements and ten aerodynamic points, the full, four-bladed case that originally ran in 154.552 minutes, runs in 27.772 minutes with model reduction. The reduction in computation time is not as large for the identical blade models. The number of computations has been greatly reduced in the identical blade model and therefore, the benefits of having a system with fewer degrees of freedom are lessened. Still, the computations for the identical blade model with modal reduction are performed approximately three times faster that the identical blade model without modal reduction for the cases cited. The greatest reduction in computational time is from the four-bladed model with no modal reduction, which is how 2GCHAS operates today, to the identical blade model with modal reduction. The time goes from 154.552 minutes to 3.107 minutes, for a 97.99 percent reduction in computational time. The relative savings changes if vortex wake is used for the inflow model, as the current model uses no inflow.

Scope of Future Work

While the proof of concept and prototype coding is complete for the identical blade algorithm and modal reduction, full implementation of the algorithms into a comprehensive rotorcraft analysis code (2GCHAS) needs to be completed. With the use of the developed super element, the identical blade algorithm can be integrated into 2GCHAS, as well as the modal reduction algorithm. Within the super element, aerodynamics will be included, as well as such features as torque offset, precone, droop, swept tip, and a pitch link model. The implementation of the algorithms will include modifying the prototype code to meet the requirements of 2GCHAS standards. Also, the code will be organized in modular subroutines with a well-defined interface.

After the algorithms are completely integrated into the 2GCHAS code, a wide range of problems associated with comprehensive rotorcraft analysis will be tested to demonstrate the efficiency and robustness of the algorithms.

With the implementation of the algorithms described in this report, a software package, such as 2GCHAS, can provide more efficient methods of rotorcraft analysis to be applied to all new rotorcraft designs and product improvements. A more efficient analysis tool will reduce the time and thus, the design cost, of rotorcraft development.

Discussion and Conclusion

The proof of concept for efficient trim and transient response through identical blade analysis and modal reduction is successfully complete. For both identical blade and modal reduction, the resulting forces and moments at the hub, as well as the flap angle match the results from the full four-bladed analysis soon after the first rotor revolution. Also, identical blade analysis has been successfully combined with modal reduction with accurate results.

Both steps significantly reduce the computational time of rotorcraft systems with a large number of degrees of freedom. A large reduction in runtime is found with the implementation of the identical blade algorithm, and as the number of blade elements increases, the time savings increases as well. Modal reduction also contributes to the reduction in runtime of large systems. The combination of both modal reduction and identical blade analysis offers the best results, as the results are accurate and offer the largest reduction in computational time.

The introduction of a super element defined in the 2GCHAS UDE successfully reproduces the results found in FLIGHTLAB using the same model. The super element is capable of handling a ten element blade with a lag damper as well as a pitch bearing that includes a spring and damper. This super element allows for the implementation of modal reduction in 2GCHAS and offers a more efficient trim procedure, as the system matrices are calculated only once verses once per time step.

The success of the efficient trim and transient response prototype code prompts the completion of the project by implementing a final, robust version of the code into a comprehensive rotorcraft analysis package such as 2GCHAS. The much needed reduction in runtime for complex rotorcraft systems is now available with the algorithms developed in this Phase I contract. With the completion of the integration and testing of the code into 2GCHAS, the ability to analyze rotorcraft systems efficiently can be extended.

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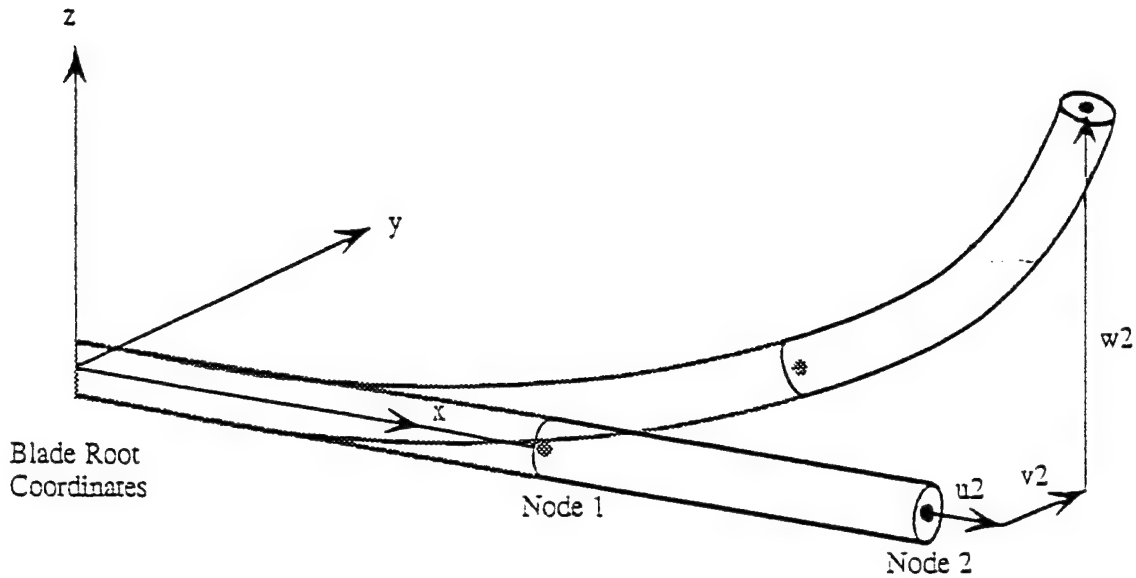

Fig. 1: Element Degrees of Freedom in Blade Root Coordinates

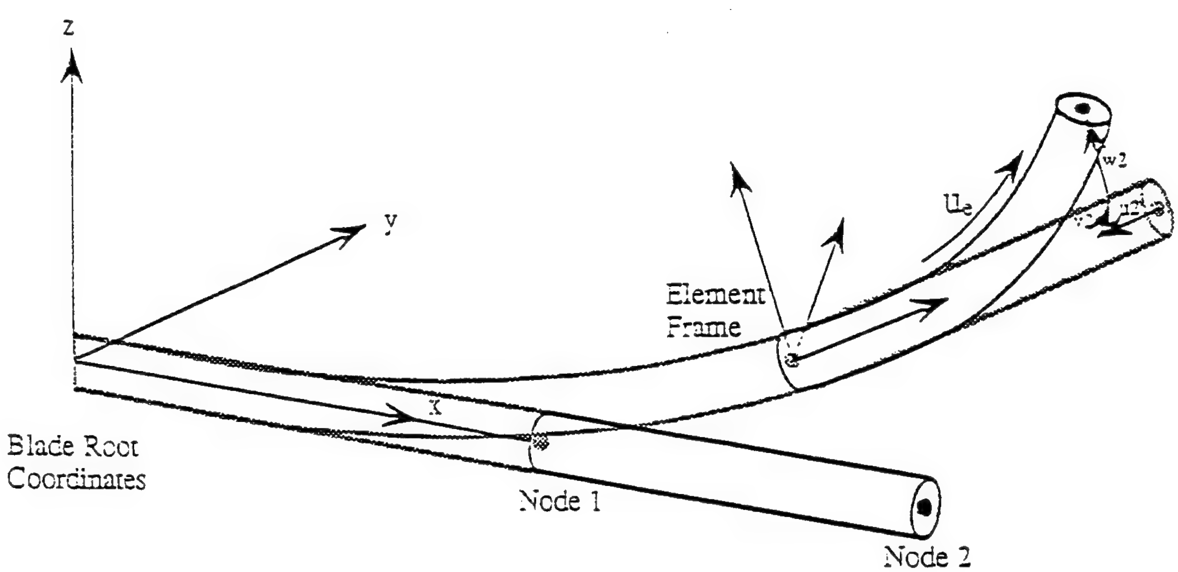

Fig. 2: Element Degrees of Freedom in Element Root Coordinates

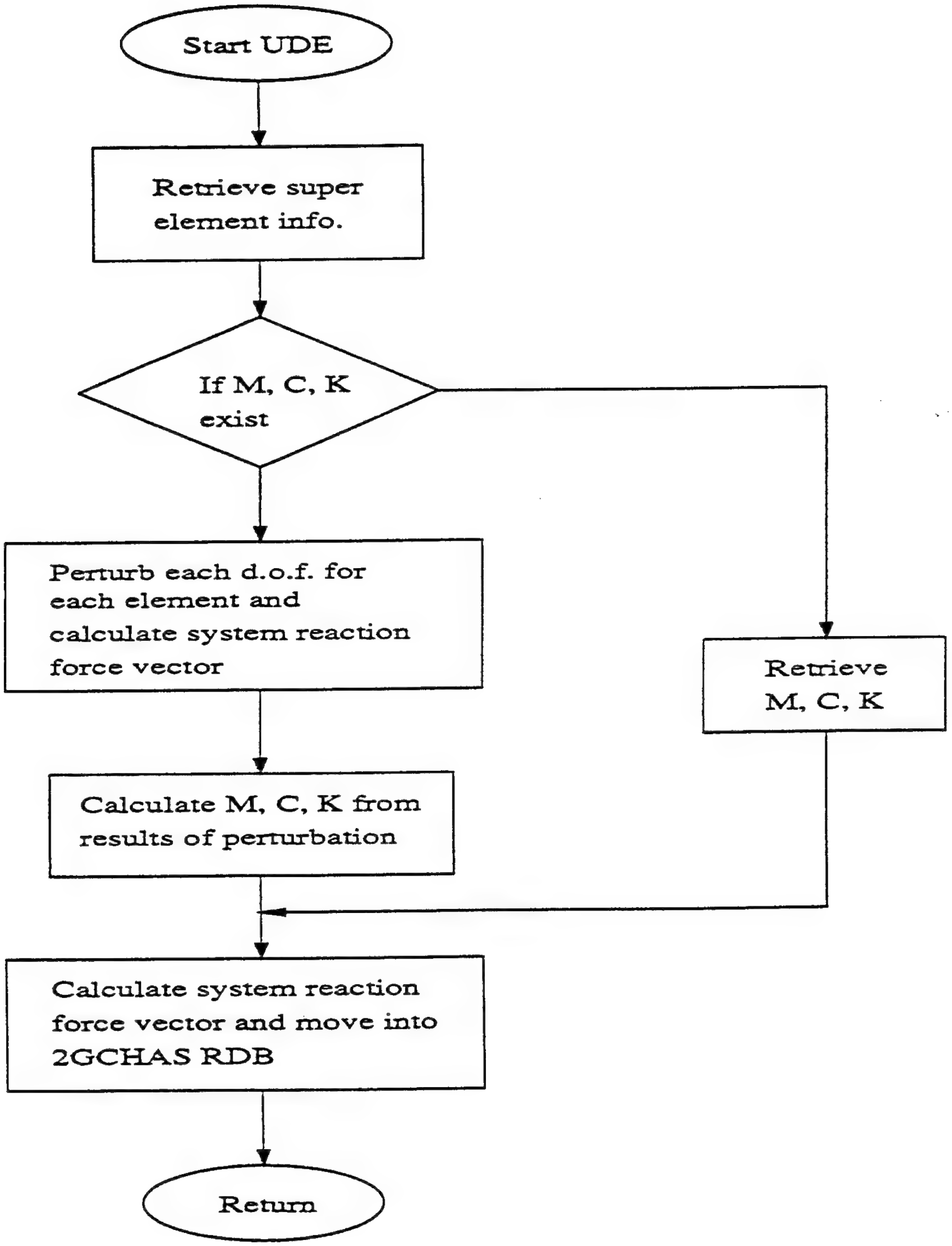

Figure 3: Super Element Flow Chart in 2GCHAS User Defined Element.

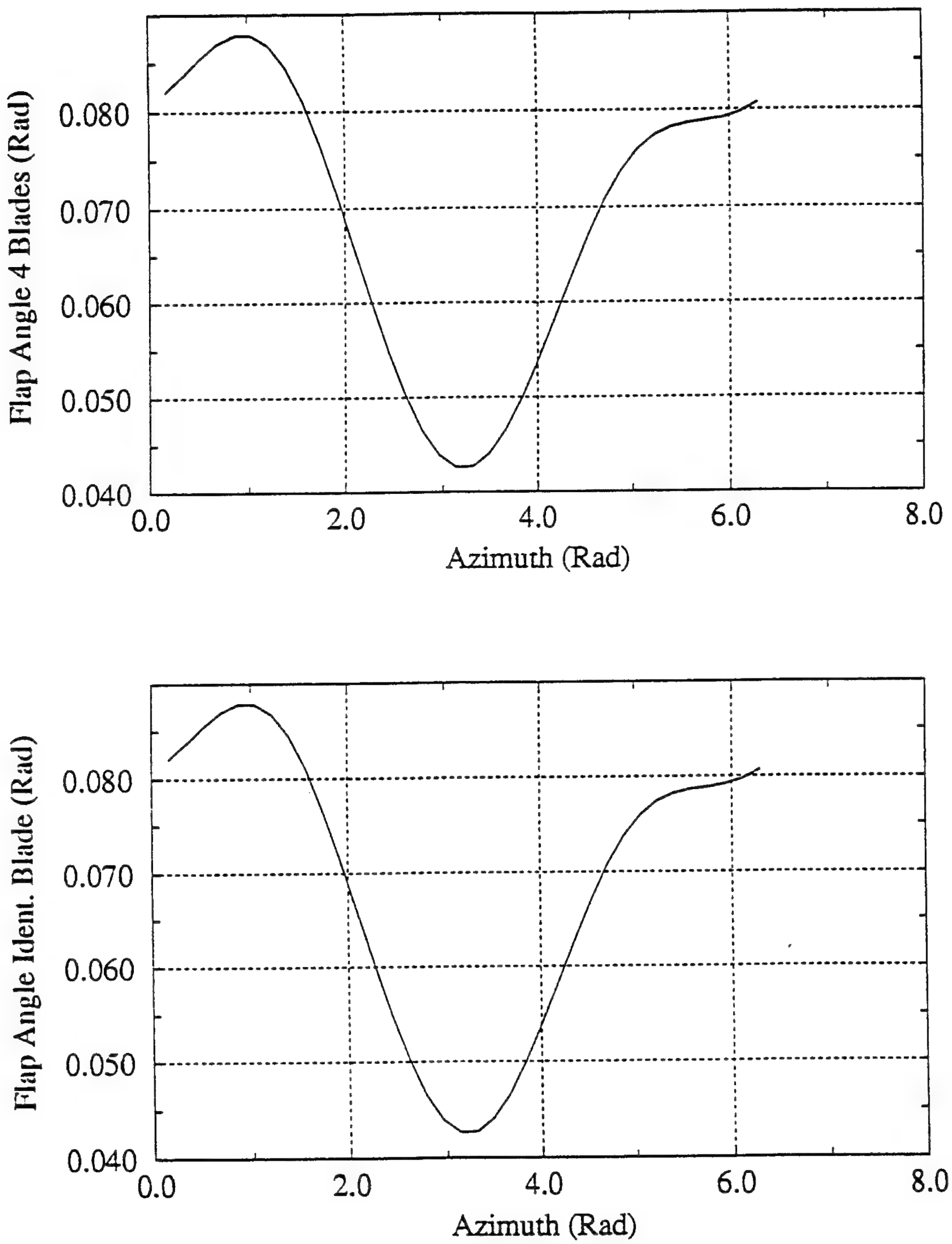

Figure 4: Comparison of Flap Angles for Identical Blade and a Rigid Four-Bladed Rotor in 2GCHAS. Model Includes Rigid Fuselage and Four Rigid Blades in Forward Flight with Uniform Inflow.

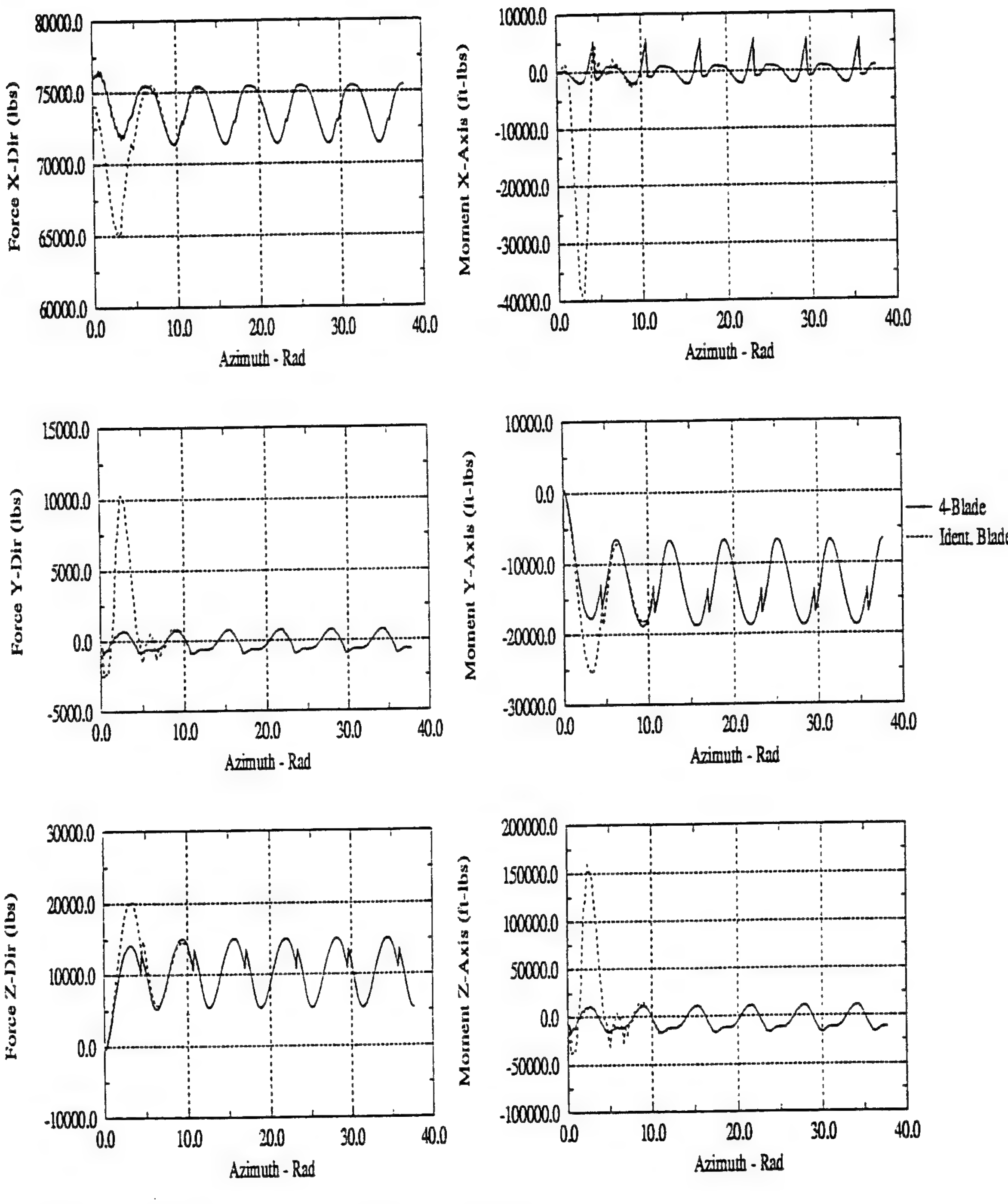

Figure 5: Comparison of Forces and Moments at the Hub for Identical Blade and Four-Bladed Rotor in FLIGHTLAB. Model Includes Rigid Fuselage and Four Blades Modeled with Ten Non-Linear Beam Elements and Ten Aerodynamic Points. The System is in Forward Flight at 104 knots.

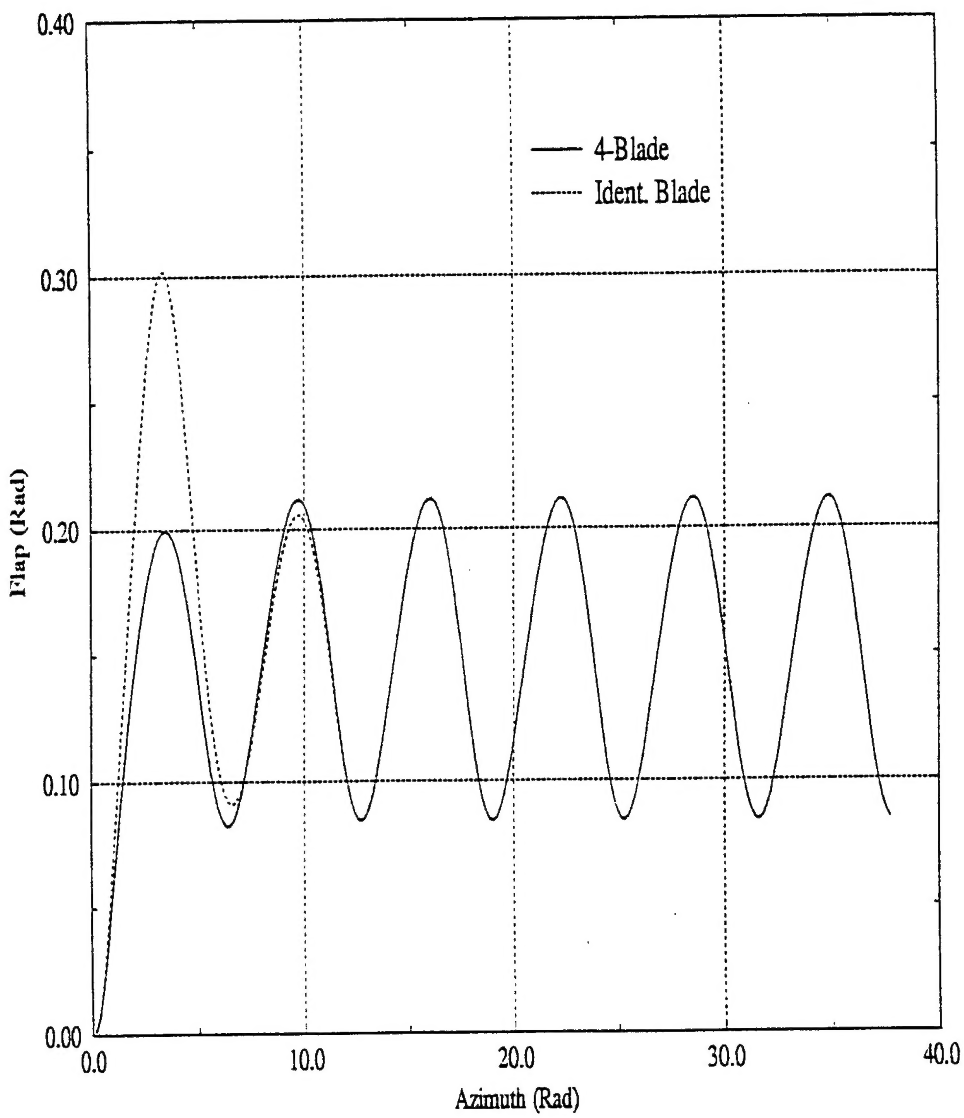

Figure 6: Comparison of Flap Angles for Identical Blade and Four-Bladed Rotor in FLIGHTLAB. Model Includes Rigid Fuselage and Four Blades Modeled with Ten Non-Linear Beam Elements and Ten Aerodynamic Points. The System is in Forward Flight at 104 knots.

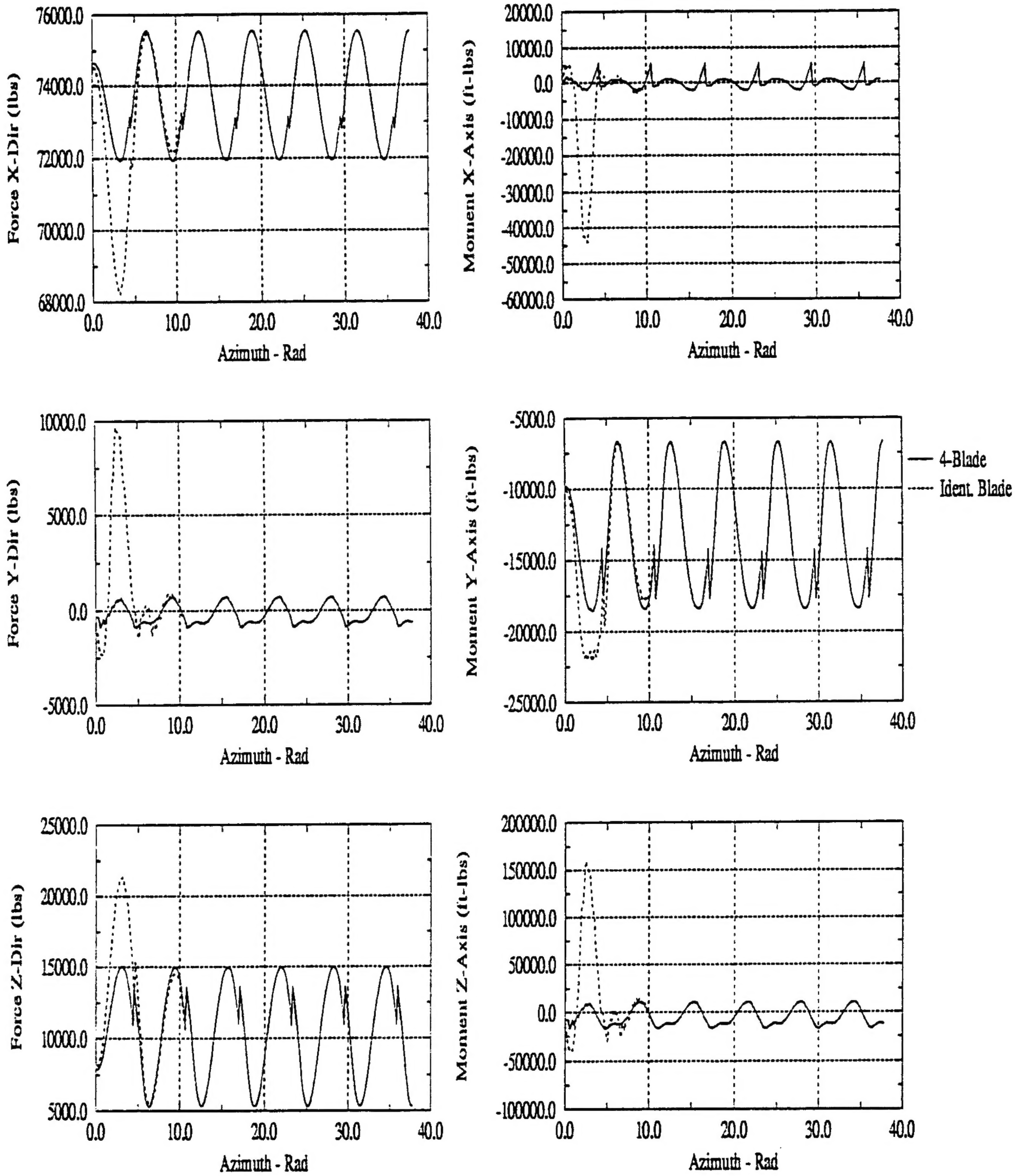

Figure 7: Comparison of Forces and Moments at the Hub for Identical Blade and Four-Bladed Rotor with Modal Reduction in FLIGHTLAB. Model Includes Rigid Fuselage and Four Blades Modeled with Ten Non-Linear Beam Elements and Ten Aerodynamic Points. The System is in Forward Flight at 104 knots.

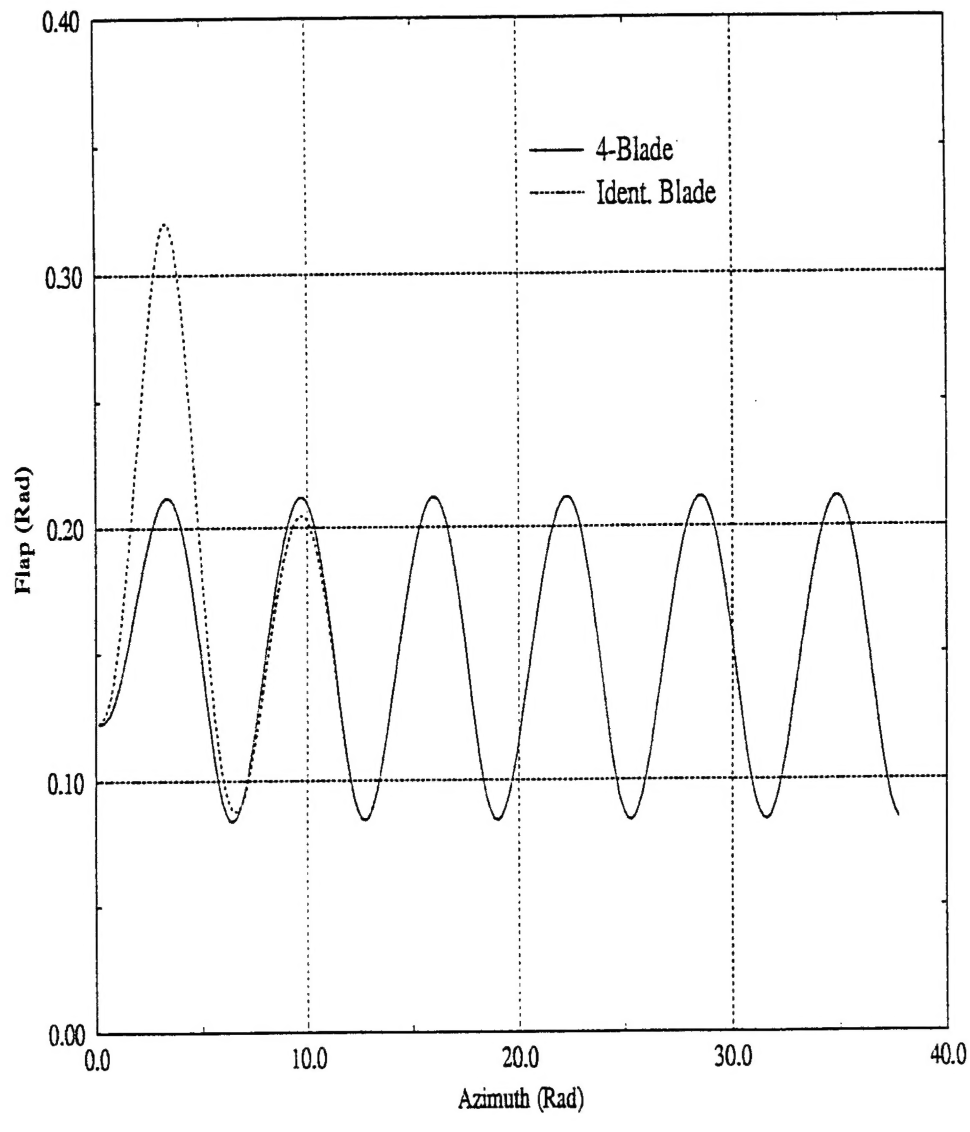

Figure 8: Comparison of Flap Angles for Identical Blade and Four-Bladed Rotor with Modal Reduction in FLIGHTLAB. Model Includes Rigid Fuselage and Four Blades Modeled with Ten Non-Linear Beam Elements and Ten Aerodynamic Points. The System is in Forward Flight at 104 knots.

Table 1: Eigenvalues from 2GCHAS with User Defined Element and from FLIGHTLAB for a Two Element Blade. The Eigenvalues Are Equal Out to the Fourth Significant Digit.

FLIGHTLAB Eigenvalues	2GCHAS Eigenvalues
-28.417 ± 167.789	-28.417 ± 167.789
0.000 ± 464.482	0.000 ± 464.482
0.000 ± 465.268	0.000 ± 465.268
-89.374 ± 2179.362	-89.374 ± 2179.362
0.000 ± 3104.306	0.000 ± 3104.306
0.000 ± 3104.426	0.000 ± 3104.426
0.000 ± 3477.815	0.000 ± 3477.815
0.000 ±10582.078	0.000 ±10582.078
0.000 ±10582.115	0.000 ±10582.115
0.000 ±15905.509	0.000 ±15905.509
0.000 ±24967.649	0.000 ±24967.649
0.000 ±24967.664	0.000 ±24967.664
0.000 ±51623.044	0.000 ±51623.044

Table 2: Times for Identical Blade and Modal Reduction in FLIGHTLAB. Results are in Real Time.

Modal Reduction	Number of Element/Aero pts.	4-Bladed Time (Min)	Identical Blade Time (Min)
None	3	16.684	1.830
3 modes	3	5.231	1.240
None	10	154.552	9.475
10 modes	10	27.772	3.107